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Performance of an Aerial Variable-Rate Application System with a Hydraulically Powered Chemical Pump and Spray Valve

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Abstract. *The performance was evaluated for a variable-rate system that consisted of a SATLOC M3 with AirTrac software with WAAS corrected DGPS (5 Hz position update) and an AutoCal II automatic flow controller. This system was installed on an Air Tractor 402B equipped with an auxiliary hydraulic package that powered the spray pump and spray valve. Spray deposition position error was evaluated by direct field observations of water sensitive cards while traveling east to west and north to south across rate change boundaries. Data from the AutoCal automatic flow controller and an improved flow meter circuit (10 Hz output with flowrate and time) was used to evaluate flow controller error and variable rate system error while making applications to a series of four management zones (each 81 m long; 28, 47, 56, and 37 L/ha). Water sensitive card observations showed that average spray deposition position error magnitude was 5.0 m when traveling east to west and was 5.2 m when traveling north to south. Statistical analysis indicated that direction of travel had a non significant effect on the magnitude of spray deposition position error. Flow controller error and variable rate system error was evaluated from data collected while making applications to a series of four management zones (each zone required approximately 1.2 s) with application rates of 28, 47, 56, and 37 L/ha. Areas under time plots of required and actual flowrates were compared and indicated flow controller error ranging from -1.0 to 2.1 percent with an average of 0.77 percent. Variable rate system error due to rate change timing was evaluated by comparing required rates from the system to required rates from the prescription. Area under time plots of these variables showed that average rate timing error for six application passes ranged from -9.1 to 1.4 percent with an average of – 3.04 percent.*

Keywords. *aerial application, variable rate application, precision application, automatic flow control*

INTRODUCTION

Variable-rate technology has been available to aerial applicators for several years, but very little performance information has been published to describe how well it works. The basic concept on which these systems were based was to combine the function of automatic flow control and swath guidance with the added capability of reading 'prescription' files that defined management zones and their associated properties (i.e. application rate and boundaries) within the fields being sprayed. The swath guidance system used a Global Positioning System (GPS) to determine current position and ground speed of the spray plane and then referenced the prescription file to determine the required application rate at that position. Speed and rate were then communicated to the flow control, which computed the required boom flow rate and adjusted the actual flow to the required rate. Aerial variable rate systems must respond to rate changes very quickly and accurately in order to succeed in placing the correct rate of spray material in each management zone.

Aerial variable-rate systems vary in the technology used to implement the system. Two companies offer total systems for aerial variable-rate application and they are Satloc, LLC [1] of Scottsdale, AZ (www.satloc.com), and Del Norte Technology, Inc. of Euless, TX (www.delnorte.com). The Satloc system components include the Satloc M-3 with AirTrac software and the AerialAce flow controller. The Del Norte system components include the DGPS Flying Flagman and the Target Flow variable rate option. Both systems are similar in that they require a flow meter, a GPS receiver, and an electric ball-valve to control boom flow rate. Other versions of variable rate systems usually make use of the swath guidance systems mentioned above in conjunction with a different flow controller or a different technology for controlling the flowrate. Houma Avionics, Inc. of Houma, LA, offers a flow controller (AutoCal II) that interfaces to the Satloc M-3 or the Del Norte DGPS Flying Flagman and controls boom flowrate by controlling the spray pump output. In this system, the spray pump is driven hydraulically from an engine-driven hydraulic power pack and an electrically operated servo-valve controls the speed/output of the spray pump with a signal from the AutoCal II. The spray valve is actuated with an electrically-controlled hydraulic cylinder operated by the pilot. The spray valve is fully opened (no bypass flow) when the plane enters the field to be sprayed and the flow control adjusts the pump's output to the required flowrate for the application rate specified for each management zone.

Evaluation of aerial variable-rate systems should involve the three primary aspects of their performance: a) the accuracy of rate-change position relative to management zone boundaries, b) response time required to achieve the rate change and c) the accuracy of the rate applied. Rate-change position error includes the uncertainty of the GPS system's capability for locating the zone boundary under dynamic conditions, the uncertainty of the variable-rate system for initiating rate change at the proper time, and the uncertainty of the application parameters, which include release height, ground speed, wind speed, and wind direction.

Aerial variable-rate application systems utilize a GPS receiver to guide the pilot along the proper spray swath, monitor ground speed and identify management zone boundaries where

[1] Trade names are mentioned solely for the purpose of providing specific information. Mention of a trade name does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture, or ASAE, and does not imply endorsement of the product over products not mentioned.

application rates may change. The system must coordinate the processing of information from the GPS receiver, prescription file, flow meter, and spray system parameter values set by the pilot in order to implement control commands in a timely way that results in a successful spray job. Therefore, GPS receiver performance is only one component of the variable rate system performance and its performance may not reflect the overall performance of the system.

The dynamic performance of GPS receivers has been studied by Taylor et al. (2004) and Han et al. (2004), but the emphasis was on cross-track error. This aspect of position error was evaluated since the majority of applications for GPS systems in agriculture are related to machine guidance along parallel tracks. These studies used a Real Time Kinematic (RTK) GPS system with centimeter level position accuracy as a reference for comparison to other GPS receivers mounted on the same platform as it was traversed over a test track. Taylor et al. compared a GPS receiver with dual-frequency correction to a receiver operated in autonomous mode (no differential correction) over a 24 hour period at two different speeds and in opposite directions of travel on a fixed fixture (railroad). Differential correction reduced mean cross-track error from 1.348 m to 0.171 m. Han et al. compared the cross-track position error of eight GPS receivers as the test platform was driven on a straight-line in the north-south direction to make six parallel passes that were 305 m (1000 ft) long. A total of 68 tests were made at different dates, different times of day, and at four different ground speeds (1.34, 2.24, 3.58, and 5.36 m/s). Four of the systems evaluated used the wide area augmentation signal (WAAS) for differential correction. Average cross-track error for the WAAS corrected units ranged from 8 to 39 cm with a mean error of 16.5 cm. The lowest speed test required approximately 30 minutes for completion compared to approximately 9 minutes for the highest speed. Cross-track error tended to be larger for the lowest speed and this was attributed to the greater time required for these test; however, a detailed analysis of speed effects on position accuracy was not a part of the study.

The identification of management zone boundaries crossed by the spray plane is a critical function of the aerial variable-rate system because rate changes occur at these positions and the plane is typically traveling at ground speeds of 209 to 240 km h^{-1} (130 to 150 miles h^{-1}). Smith and Thomson (2005) evaluated the position latency of the GPS receiver used in the SATLOC swath guidance system which is a component of their variable-rate system. A light-sensing circuit was mounted on the plane and interfaced to the swath guidance system such that a record was introduced into the system data log when the plane passed over a vertical light beam emanating from a reference point on the ground with known position coordinates. The data log record containing plane position coordinates associated with the light beam was then compared to the reference point position, and the distance between the points (measured in the direction of flight) was considered to be the position latency. Cross-track error was not considered because the airplane could not be confined to a specified flight line. This study found that the dynamic position latency (based on logged data from the system) was 7.9 m on average when traveling north or south and -4.5 m when traveling east or west. Increasing ground speed by 12 percent tended to increase magnitude of position latency less than 1 meter.

Many studies have shown that application rate errors associated with boom injection systems result from transport lag (Zhu et al.,1998; Tompkins et al., 1990; and Miller and Smith, 1992). Transport lag is a function of the solution velocity and the volume of liquid in the hose between the injection point and the nozzle (Rockwell and Ayers, 1996). In pressure-based systems, transport lag refers to the time lapse between the request for change in application rate and the attainment of the new rate. Al-Gaadi and Ayers (1994) also classified the influence of lag on system response as delay time, which is the time required for the system to reach 10% of a step input, and response time, which is the time required to go from 10% to 90% of a step input. The sum of delay and response times is classified as reaction time (Rockwell and Ayers, 1996). Anglund and Ayers (2003) investigated the performance of a ground sprayer applying chemicals at constant and variable rates. Tests were performed on pressure-based spray systems as well as injection systems. Transport lag for pressure-based variable rate systems was approximately 2 s due to GPS signal lag and control valve response lag. On injection type variable rate technology, the active ingredient lag time varied for each nozzle and ranged from 15 to 55 s. Results showed an average application rate within 2.25 % of the desired rate.

OBJECTIVE

The objective of this study was to evaluate position error of spray deposits relative to management zone boundaries where rate changes occur, flow controller accuracy, and variable rate controller accuracy for an aerial variable-rate system.

MATERIALS AND METHODS

The aerial variable-rate system used in this study consisted of a SATLOC M-3 swath guidance system running AirTrac software that was designed to perform variable-rate application. The SATLOC GPS receiver used WAAS for differential correction and updated position at 5 Hz. The AutoCal II automatic flow controller received ground speed and application rate from the SATLOC system and adjusted the spray pump output to deliver the required flow to the boom based on speed, rate, and swath width. The spray system on the Air Tractor 402B was customized by installing a hydraulic power pack (Ag Air Systems, Inc., Bend, OR) that featured an engine driven hydraulic pump, a hydraulic motor for driving the spray pump and a hydraulic cylinder to actuate the spray valve. Hydraulic power to the spray pump was controlled with an electrically operated hydraulic servo valve from signals generated by the flow controller. The spray valve was also operated electrically with a toggle switch mounted on the aircraft control stick. Variable rate operation required the development of a prescription file that specified the areas of the field that receive different rates and the rates that they were to receive. The function of the SATLOC was to keep up with the position of aircraft using the on-board GPS receiver, guide the pilot to the spray swath to be sprayed, and communicate the ground speed and required application rate to the flow controller in a timely way that synchronizes rate changes with management zone boundaries. The functions of the flow controller are to receive the speed and rate updates, to calculate the required flowrate, to read the actual flowrate from the flow meter and to adjust the spray pump to achieve the required rate.

Performance of the system was evaluated using data generated by the automatic flow control system, data from a circuit designed to read the flow meter at a 10 Hz rate and time-stamp each record using a real-time clock, and data from water-sensitive cards to physically define the spray deposition position relative to rate-change-boundaries (RCB). The flow controller generated data records (serial output) at irregular time intervals depending on which control loop was being used in the controller software. These records were captured to the hard drive of a notebook computer using Windows Hyperterminal software and included values of actual flowrate, required flowrate, and ground speed. The circuit for reading the flow-meter (FMC) produced records at 0.1 s intervals that included the current time and flowrate to the boom, and this output was captured with Pocket-PC using ZTERM software. Turn-ON/Turn-OFF position error was measured with water-sensitive cards supported on horizontal samplers and positioned at 2 m intervals on either side of the RCB for a distance of 20 m. Position error was also estimated from FMC timing data and ground speed data from the AutoCal II.

Flow meter readings by the FMC were based on the measurement of elapsed time between consecutive turbine-wheel blade passes through the magnetic field of the flow meter proximity sensor. This time was measured by gating a 250 kHz signal generated by a crystal-controlled oscillator to a counter during this period. Simulations of the flow meter signal with a signal generator demonstrated that the circuit was accurate within 1 period of the 250 kHz signal; therefore, the interval between blade passes was measured with an accuracy of four microseconds. The time required for one blade pass could be converted to gallons per minute by using the calibration constant of 45.47 blade passes per gallon. A Basic Stamp micro-controller (BS2p-24, Parallax, Inc., Rocklin, CA) was used to read the flow-meter and real-time-clock. The raw data were converted to desired units and then output through a serial port at a 10 Hz rate for capture by the Pocket-PC. A 10 Hz timing signal, generated by the oscillator, was applied to an input pin of the micro-controller to control the output interval of the data records.

The test area used for evaluating the aerial variable-rate system was established on an area that was approximately 506 x 271 m (1660 x 890 ft). This area was land-formed and seeded to Bermuda grass such that spray test sampler lines could be established relative to any wind direction that might exist. A prescription was established for testing purposes that included management zone sizes ranging from 81 m to 162 m in length and application rates ranging from 0 to 56.1 L/ha (fig. 1). A 0 L/ha rate was assigned to buffer zones on both ends of the prescription area to provide time for the spray boom to be turned on/off by the pilot when entering or exiting the prescription area. Corners of the rectangular management zones were located on the ground using Trimble MS-750 RTK receivers with Sitenet 900 radio (cm level accuracy) referenced to a base station positioned over the U. S. Coast and Geodetic Survey Satellite Triangulation Station #133 that is established 3.68 km from the test area. After locating the management zone corners, steel rods (1.9 cm diameter x 60 cm length) were driven into the ground to permanently mark them.

Discussion of Results

Spray Deposition Position Accuracy

The aerial variable rate system was tested initially by making application passes over a rate-change boundary between two management zones defined by the prescription and observing spray deposition on water sensitive cards (3 x 5 cm). A lead time of 0.5 s was set in the AirTrac software to facilitate the change in application rate at the proper position relative to the RCB. Water sensitive cards were positioned relative to the zone boundary and supported on horizontal sampling stands spaced at 2 m intervals and aligned with the direction of flight. Figure 2 shows spray deposition position relative to the rate change boundary when making applications in an east to west direction with the application rate changing from 0 L/ha to 56 L/ha when the boundary was located at the 20 m position. A total of 10 spray passes were made with identical setup parameters to evaluate the variability and magnitude of deposition

position error. The deposition position error ranged from -18 m to +4 m where the negative error denotes spray initiation after reaching the rate change boundary and the positive error denotes early initiation of spray. Deposition position error magnitude averaged 5.0 m for the 10 spray passes and the standard deviation of error magnitude was 6.9 m. The algebraic average (including sign) of deposition position error was – 3.8 m. Average ground speed for these spray passes was 63.9 m/s; therefore, the system tended to delay spray initiation by 0.05 s, on average. It would be tempting to increase the lead time in the software by 0.05 s (to 0.55 s) to compensate for this delay, but the system performed very well except for a few large errors. When individual spray passes are considered, one finds that seven of the ten spray deposition errors had magnitudes of 4 m or less with three of them being zero. These seven passes had errors that were evenly split between early and late initiation such that their algebraic average was zero. Therefore, lead time appears to be correct. The large errors observed for the other three spray passes (-8, -18, and -12 m) are possibly due to the slow GPS position update interval of 0.2 s during which the aircraft travels 12.8 m. Rate change communication and response of the flow controller to the rate change is another possible source of this error. With the current setup there is no way to evaluate the time required for the flow controller to respond to a new application rate communicated to it by the SATLOC system.

A second test of spray deposition position error was made with the flight line in the north-south direction due to previous test results (Smith and Thomson, 2005) that demonstrated differences in dynamic GPS position latency with respect to direction of flight. In this test the applications were made while traveling from the north to the south and crossed a rate change boundary where application rate changed from 0 L/ha to 28 L/ha. Setup for the test was similar to the east-west test above except that 25 samplers were used instead of 21 in the previous test and five applications were made instead of ten. Results from this test are shown in figure 3. Spray deposition position error ranged from -8 m to 6 m with an algebraic average of -2.8 m and an average magnitude of 5.2 m. The standard deviation of deposition position error magnitude was 2.3 m.

A statistical analysis of deposition position error magnitude from these tests (north-south versus east-west) showed no significant differences in the treatment means ($F=1.78$; $P>F = .2528$). This result means that the variable rate system response to rate change boundaries is similar for all directions of flight; therefore, a constant lead time can be used. The effect of flight direction on dynamic GPS position latency discovered in a previous study must have been the result of data logging logistics associated with software execution. Evidently, the variable rate system does a better job of associating spray rates with physical positions on the ground than it does for associating position coordinates in data log records with physical positions on the ground.

Flow Controller Accuracy

Data from the FMC and the AutoCal II (captured while spraying the west lane of the prescription) were combined to plot the required and actual flow rate versus time. A total of six spray passes were made in alternating directions and typical plots while traveling in each direction are presented in figures 4 and 5. The required application rates are mirror images of each other since the applications were made from opposite directions, but characteristic differences were observed in responses to the initial rate changes. Flow controller response to the zero to 28 L/ha (3 gal/acre) rate change was overdamped (fig. 4), but the response to the zero to 37 L/ha (4 gal/acre) rate change did not typically show this characteristic (fig. 5). This type of response can be explained as the combined effect of the control approach used and the type of spray pump.

The basic approach used by the flow controller was to adjust the pump output to achieve the required flowrate. As the prescription area was entered, the pilot would manually toggle a switch on his flight control stick to completely open the boom valve. This valve position did not allow recirculation to the hopper so boom flow could be controlled by adjusting the pump output. Pump output was controlled by the application of voltages (proportional to the flowrate required) to a hydraulic servo valve that controlled the flowrate of hydraulic fluid to the hydraulic motor driving the spray pump. With the system configured in this way, a zero application rate requirement caused the pump to be turned off, but the boom valve remained in the open position. Rate change to a non-zero value required the spray pump to overcome the static condition of the spray mix and get it moving through the plumbing and out of the boom. A centrifugal pump was used to pump the spray-mix and the efficiency of this type of pump increases as its rotational speed increases. Therefore, more time was required to achieve a change (from zero) of 200 L/min than was required to achieve a 250 L/min change due to the lower efficiency associated with the lower rotational speed of the centrifugal spray pump. The overdamped response was not apparent at required flowrates of 250 L/min and above. These results have prompted the manufacturer to consider a revised approach for flow control that keeps the pump operating and closes the boom valve to achieve zero-flow requirements. With the boom valve in the closed position, flow to the boom is shut off and the pump output recirculates to the hopper. This approach has the advantages of maintaining fluid momentum through the pump and having non-zero pressure available for initiating spray when the boom valve is opened.

Direct measures of the average flow controller accuracy were made by numerically integrating the area under the time plots of required flowrate and actual flowrate as illustrated in figures 4 and 5. Table 1 presents the areas under these curves and the average error of the flow controller for each spray pass. Average error for each pass ranged from -1.0 to 2.1% and the overall average error for the six passes was 0.77%. These errors reflect the ability of the flow controller to maintain the required rates communicated to it by the variable rate system. Considering that the four management zones were traversed in approximately 1.2 s each and that each zone had required rates ranging from 28 to 56 L/ha, an average application error of less than 1% is excellent.

Variable Rate Controller Accuracy

Flowrate error relative to the timing of rate changes with respect to management zone boundaries should be attributed to the variable rate controller rather than the automatic flow controller. This type of error is the result of timing associated with determination of position and ground speed, determination of prescription file application rates for approaching management zone boundaries, and communication of rate changes to the flow controller. If these processes are performed within a consistent time frame, lead time in the software can be used to compensate for them and allow the rate changes to be synchronized with the physical boundaries of the management zones. This type of error can be measured by comparing the required flow rates defined by the variable rate controller to the rates required by the prescription. Numerical integration of the area under time plots of these relationships is presented in Table 2. A comparison of prescription rates to the variable rate system rates communicated to the flow controller revealed that rate error ranged from -9.1 to 1.4% for the 6 spray passes. Average error across the 6 spray passes was -3.04%. This type of error was almost 4 times the magnitude of the flow controller error and represented the combined influence of factors mentioned above that affected the timing of rate changes relative to the management zone boundary. One possible source of additional error that is included in this type of error, but could not be evaluated with the current setup, was delay in flow controller response to rate changes communicated to it by the system. No indication of controller delay was observed in the captured data; however some delay could have been present.

Summary and Conclusions

The performance was evaluated for a variable rate system that consisted of a SATLOC M3 with AirTrac software and a WAAS-corrected DGPS (5 Hz position update) and an AutoCal II automatic flow controller. This system was installed on an Air Tractor 402B equipped with an auxiliary hydraulic package that powered the spray pump and spray valve. Spray deposition position error was evaluated by direct field observations of water sensitive cards while traveling east to west and north to south across rate change boundaries. Data from the AutoCal automatic flow controller and an improved flow meter circuit (10 Hz output with flowrate and time) was used to evaluate flow controller error and variable rate system error while making applications to the west lane of the test area prescription (4 zones, 81 m long; 28, 47, 56, and 37 L/ha). Water sensitive card observations showed that average spray deposition position error magnitude was 5.0 m when traveling east to west and was 5.2 m when traveling north to south. Statistical analysis indicated that direction of travel had a non-significant effect on spray deposition position error magnitude. Flow controller error and variable rate system error was evaluated from data collected while making applications to a series of four management zones (each zone required approximately 1.2 s) with application rates of 28, 47, 56, and 37 L/ha. Areas under time plots of required and actual flowrates were compared and indicated flow controller error ranging from -1.0 to 2.1 percent with an average of 0.77 percent. Variable rate system error due to rate change timing was evaluated by comparing required rates from the system to required rates from the prescription. Area under time plots of these variables showed that average rate timing error for six application passes ranged from -9.1 to 1.4 percent with an average of – 3.04 percent.

Conclusions reached as a result of this study were:

1. Spray deposition position error magnitude relative to rate change boundaries was approximately 5 m on average.
2. Spray deposition position error magnitude was not significantly affected by direction of flight.
3. Flowrate error attributed to the automatic flow controller was 0.77 percent on average.
4. Flowrate error associated with rate change timing was -3.04 percent on average.

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Table 1. Area under flowrate vs. time curves comparing accuracy of flow controller response to step changes in required flowrate as defined by the variable rate system. Data were collected while making six spray passes over a series of four management zones (each 81 m in length, requiring approximately 1.2 s) with application rates of 28, 47, 56, and 37 L/ha. Area values represent the average response for each pass and were computed by numerical integration techniques using 0.1 s time intervals.

Pass	Actual Flowrate Area [(L/min)*s]	Required Flowrate Area [(L/min)*s]	Percent Error (%)
1	1517	1506	0.7
2	1373	1349	1.8
3	1458	1429	2.1
4	1402	1416	-1.0
5	1480	1472	0.5
6	1481	1474	0.4
Average			0.77

Table 2. Area under flowrate vs. time curves comparing the required flowrate defined by the variable rate system to the required flowrate defined by the prescription. Data were collected while making six spray passes over a series of four management zones (each 81 m in length, requiring approximately 1.2 s) with application rates of 28, 47, 56, and 37 L/ha. This comparison is an indication of the error in the variable rate system relative to synchronizing rate changes with the management zone boundaries. Area values were computed by numerical integration techniques using 0.1 s time intervals.

Pass	Variable Rate System Required Flowrate Area [(L/min)*s]	Prescription Required Flowrate Area [(L/min)*s]	Percent Error (%)
1	1506	1485	1.4
2	1349	1485	-9.1
3	1429	1490	-4.1
4	1416	1483	-4.5
5	1472	1490	-1.2
6	1474	1485	-0.7
Average			-3.04

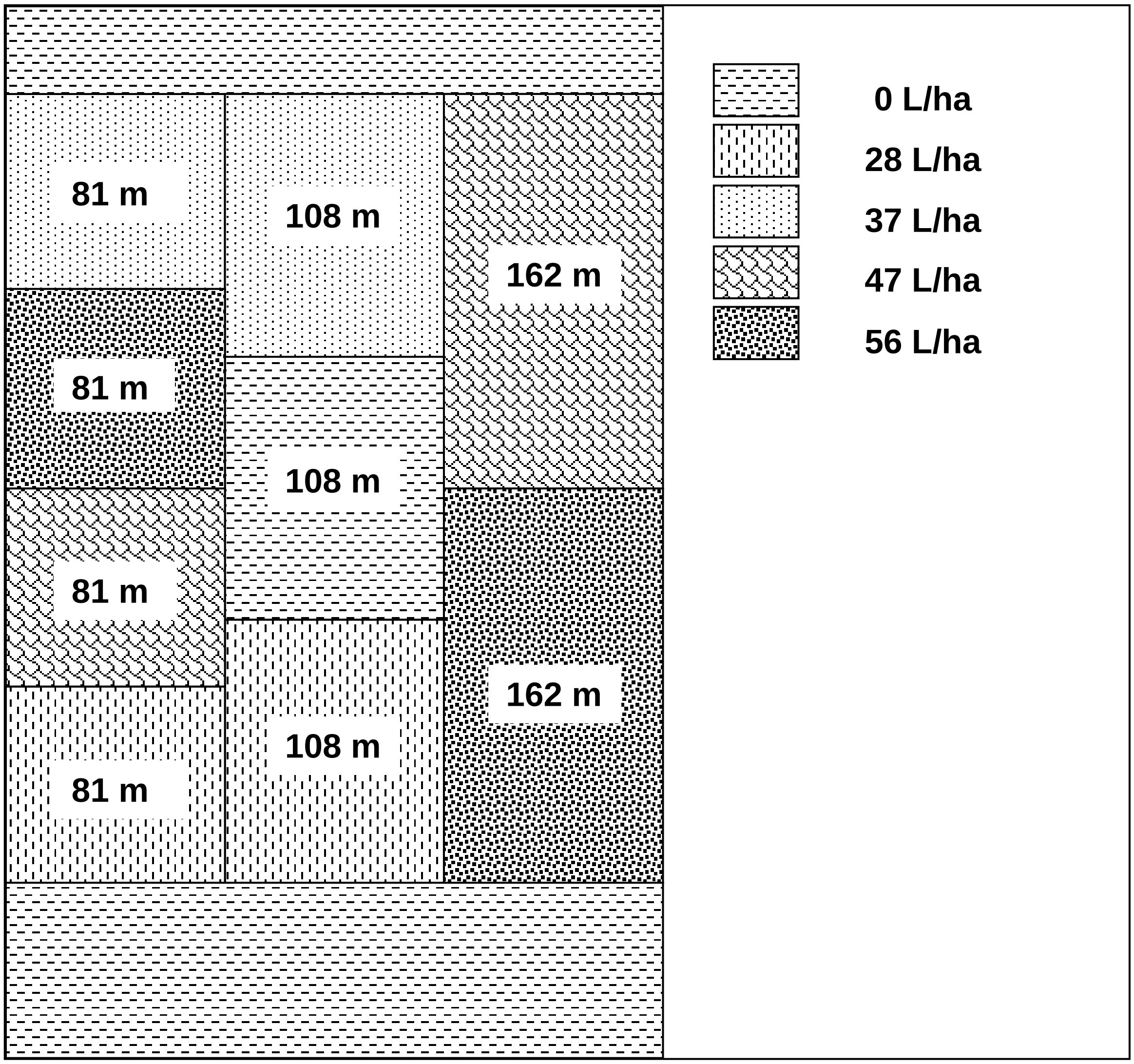

Figure 1. Layout of management zones in test area used for aerial variable-rate performance testing. The test area (324 m x 255 m) includes nine management zones laid out in three lanes (85 m wide) with lengths as indicated on the figure. Application rates ranging from 0 to 56 L/ha were assigned to zones as indicated on the legend. Buffers across the north and south ends of the test area served to give a uniform initial conditions for entering the test area from either direction.

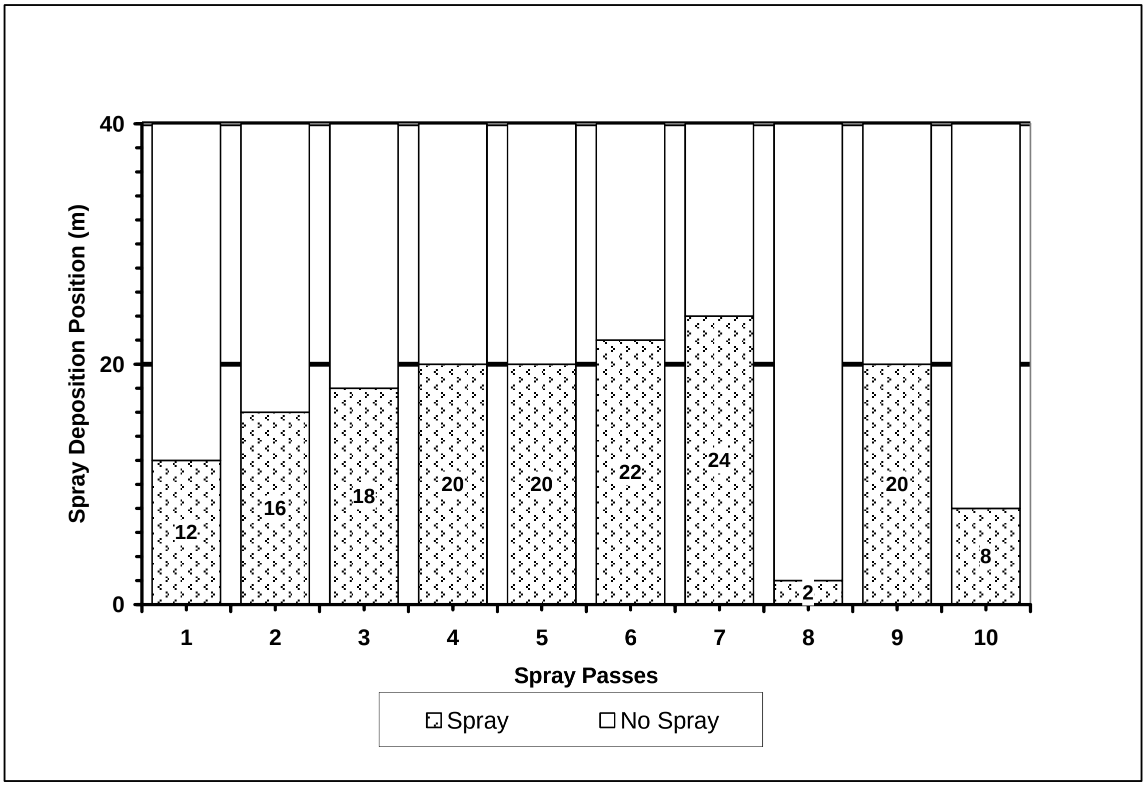

Figure 2. Spray deposition relative to a rate change boundary located at the 20 m position as determined with 21 water sensitive cards spaced at 2 m intervals. Application rate at positions less that 20 meters was 56 L/ha and positions greater than 20 m had a 0 L/ha application rate. The direction of travel for all spray passes was from the 40 m position to the 0 m position (east to west).

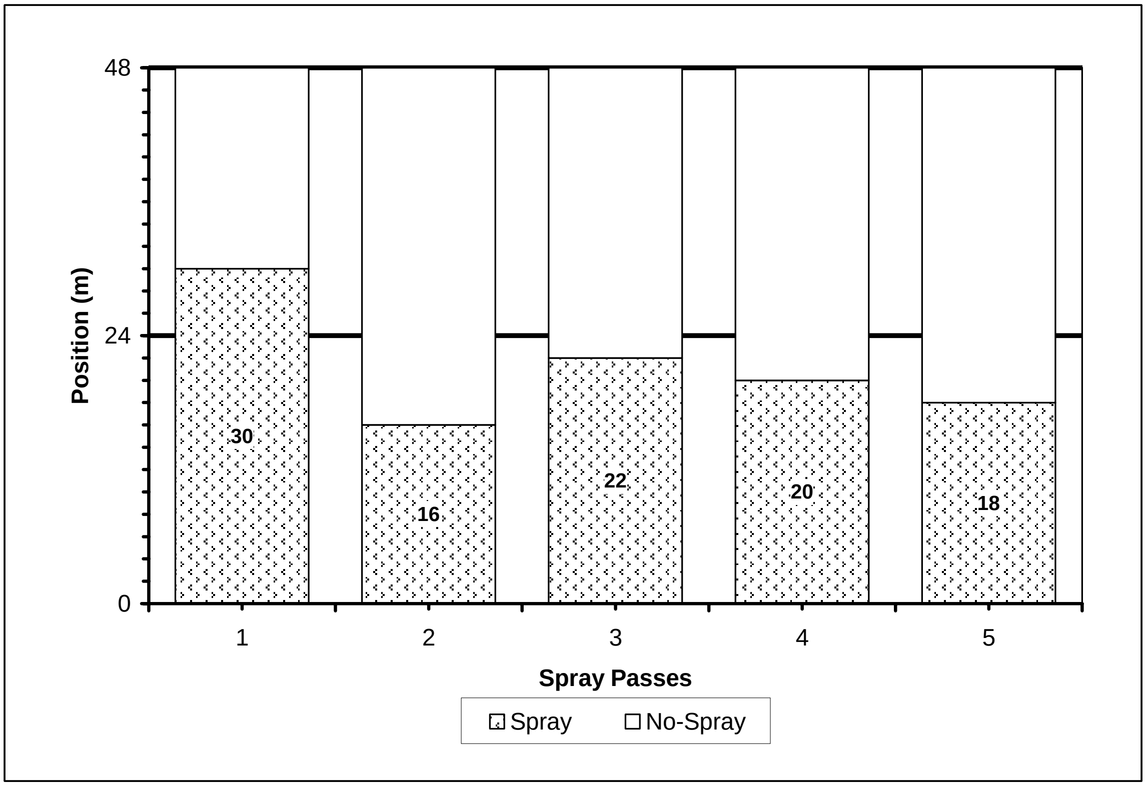

Figure 3. Spray deposition position relative to a rate change boundary located at the 24 m position as determined with 25 water sensitive cards spaced at 2 m intervals. Application rate at positions less than 24 m was 28 L/ha and positions greater than 24 m had a rate of 0 L/ha. The direction of travel for all spray passes was from the 48 m position toward the 0 m position (north to south).

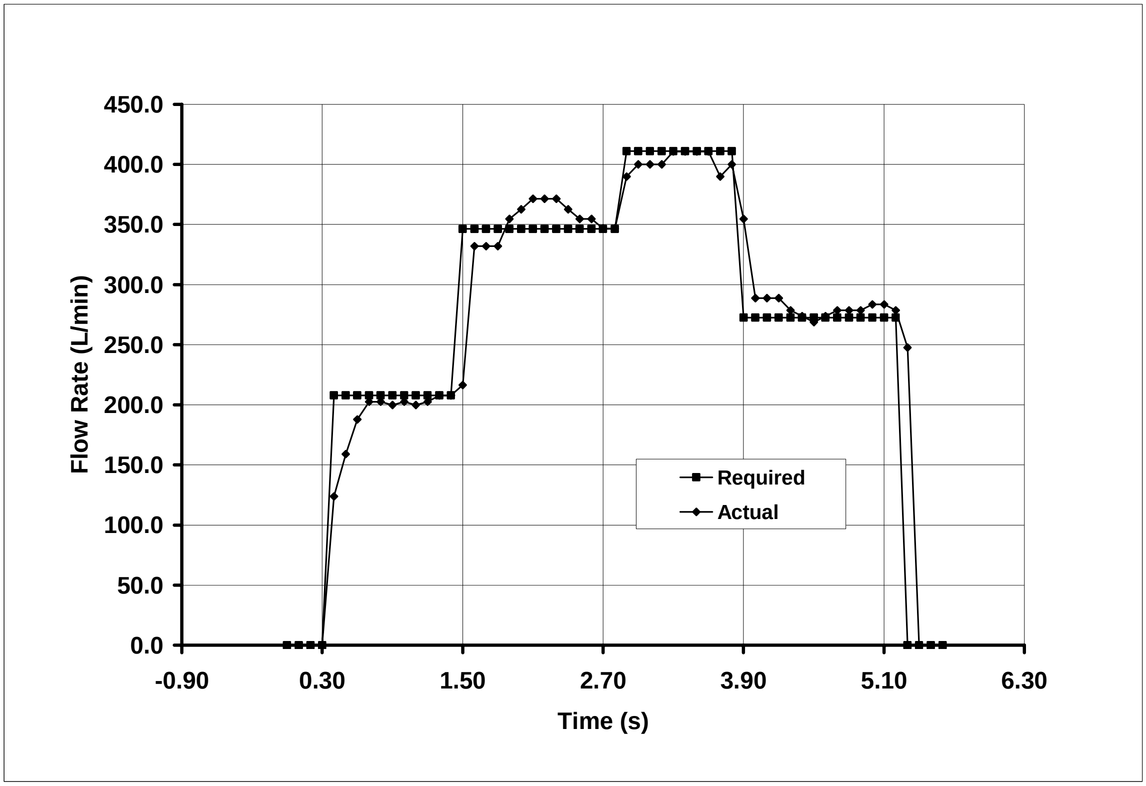

Figure 4. A typical response of actual boom flowrate to step changes in the required flow rate. These data were captured while spraying a series of four management zones with application rates of 28, 47, 56, and 37 L/ha (west lane of the prescription area [fig. 1] from the south to the north). Ground speed during this spray pass was 67.9 m/s (132 knots, 152 mile/h) and a 0.5 s lead time was used. Vertical grid lines represent management zone boundaries based on time required to travel 81 m.

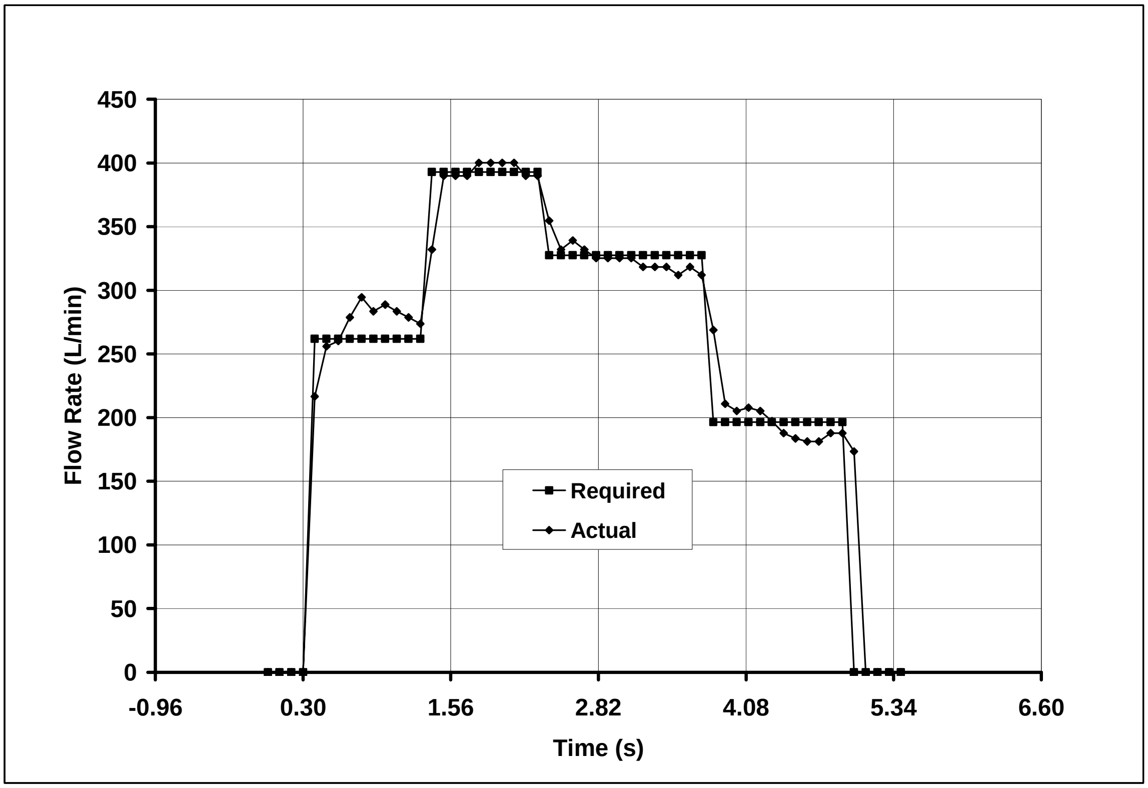

Figure 5. A typical response of actual boom flow rate to step changes in the required flow rate. These data were captured while spraying a series of four management zones with application rates of 37, 56, 56, and 28 L/ha (west lane of the prescription area [fig. 1] from the north to the south). Ground speed during this spray pass was 64.3 m/s (125 knots, 144 mile/h) and a 0.5 s lead time was used. Vertical grid lines represent management zone boundaries based on time required to travel 81 m.